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Field Application of Portable Ultrasonic Flow Meter for Well Flow Depletion Measurement

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ABSTRACT

Field observations of flow measurement difficulties using portable ultrasonic flow meters are reported in this work. Accordingly, pipe wall thickness and sensors' spacing were identified as two important sources of the in-situ flow measurement inaccuracies. Experimental tests were accomplished to evaluate the effect of input parameters on the performance of the portable ultrasonic flow meters. Iron and Unplasticized Poly Vinyl Chloride (UPVC) pipes of the outer diameters of 3, 4, and 8 inches were tested. For all tested cases, the pipe wall thickness increase would affect the ultrasonic performance more than the cases with the wall thickness decrease. A mixed effect of the sensors' spacing was observed for the changes in pipe material/dimensions. Finally, a correction equation was proposed to improve the flow measurements.

Keywords: Flow rate measurement, Taguchi Method, Sensitivity analysis, Well depletion, Well discharge reduction.

INTRODUCTION

Acquiring high-quality field data on water use is a key component for reliable water resources management. Ultrasonic Flow Meters (UFM), have been used widely for pipe flow measurements. UFM's measuring accuracy is subjected to many uncertainties such as different flow conditions, installing situations, fluid temperature, sandy water flows, and calibration methods (Caarlander and Delsing, 2000; Inoue *et al.*, 2008).

In arid and semi-arid areas, well discharge reduction is a consequence of significant groundwater table decline; hence, either partially filled pipe flow or unsteady outflow conditions took place. In such cases, the following flow conditions are possible:

1. Full pipe flow;
2. Partially filled pipe flow (Figure1-b);
3. Unsteady outflow condition.

Note that UFM is only applicable for full pipe flow condition. Besides the flow condition, many other factors have attracted the attention of the researchers affecting the performance of UFM. Pipe wall oxidation (Figure1-a), sedimentation, and inner coating are responsible for pipe wall thickness variations. It should be measured from time to time to adjust the portable flow meter input values.

Svensson and Delsing (1998) investigated the application of ultrasonic clamp-on flow meters for in situ tests of billing flow meters. Determination of the pipe data including pipe wall thickness and internal liner coating was reported as the major source of the flow measuring inaccuracies. They found that the pipe material and Reynolds number were responsible for some measurement problems. The work also indicated that clamp-on meters were not always useful for in situ testing.

In the field conditions, UFMs might be installed close to bends where the pipe is not straight. Storker *et al.* (2012) evaluated the accuracy of the portable UFMs installed downstream of the elbow. They reported an underestimation of 16% for such an installation condition. A correction equation

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Figure 1. Well pump outlet: (a) Full pipe flow, (b) Partially filled pipe flow (photos by Mohammad Bijankhan, Alborz Province, Iran).

was proposed to reduce measurement errors.

Wang *et al.* (2012) indicated that UFMs could be used reliably in the hydro-turbine intake penstock of the Three Gorges Power Station, where complex flow field conditions may affect the flow measurement accuracy.

Tawackolian *et al.* (2013) studied the temperature influence on the performance of the UFMs. They proposed a linear model of the thermal expansion effect for the tested conditions. Dutta and Kumar (2017) used an optimized fuzzy logic controller to calibrate the ultrasonic flow meter when the pipe dimensions, fluid density, and fluid temperature changed.

Su *et al.* (2021) investigated the effect of sandy water on the flow measurement accuracy of different metering devices. They used an electromagnetic flow meter, ultrasonic flow meter, and water meter to test their performance when installing on an irrigation pipe with sandy water. The results indicated that the electromagnetic flow meter was the best choice when different sediment concentrations and flow velocity condition were in use.

Among all parameters affecting the UFM accuracy, pipe wall thickness variations and limited pipe length to install the sensors have received less attention. Note that pipe wall thickness is an input parameter for the portable ultrasonic flow-meters. The surface of the old Iron pipes in Figure1-a was oxidized and resulted in a highly rough pipe surface. In such cases, the pipe wall thickness was subjected to significant uncertainty whose effect on the performance of the ultrasonic flow meter must be evaluated. Based on the field inspections, pipe-wall thickness variations were in the order of ±1 mm. Also, sensors' spacing should be adjusted according to UFM's installation type and physical characteristics of the pipe. In the field conditions, however, it was not always possible to install the sensors according to the predefined spacing values of the device. Consequently, in this paper, pipe wall thickness and sensors' spacing were identified as two important parameters affecting the flow measurement accuracy using portable UFMs. Sensitivity analyses and suitable corrections factors were proposed to improve the flow measurement accuracy.

MATERIALS AND METHODS

Experimental Tests

Experiments were performed to evaluate the effect of changes in pipe wall thickness and sensors' spacing. A pipeline setup located in the hydraulic laboratory at Imam Khomeini International University (IKIU), Qazvin, Iran, was used for the experimental tests.

Ultrasonic Flow-Meter

A portable ultrasonic flow meter equipped with clamp-on sensors was used in this study (Figure 2). It could be used for different pipe

Figure 2. Portable ultrasonic flow meter was used in this study.

materials including UPVC, steel, and cast iron. V-method was considered for the sensors' orientation (Figure 2). According to the pipe dimensions, pipe wall thickness and material, the sensors' spacing was adjusted in a straight line. Ultrasonic waves would move between the sensors and the flow rate was shown accordingly on the device screen. A portable ultrasonic thickness gauge of the model GM100 was used to measure the pipe wall thickness. The device accuracy was ±1% for the thickness range of 1.2 to 20 mm.

The ultrasonic flow meter was first calibrated to be sure of the device's performance. To this end, different experimental pipelines including UPVC pipes of the diameters of 3 and 8 inches and 4 inches of Iron-pipe were employed. To ensure uniform flow condition, pipes of at least one-meter straight lengths were considered (Figure 3). The flow was supplied by a 3,000 rpm centrifuge pump equipped with a MicroMaster-420 Siemens Drive to change the pump's rotational speed. The pipeline was supplied by a 13 m^3 reservoir. A 300-liter lateral reservoir was located at the pipe outlet to measure the flow rate by dividing the collected water volume during the associated elapsed time.

In all experimental runs, steady-state flow condition was considered. The flow was first adjusted by fixing the pump's rotational speed. Then, the discharge displayed by the Ultrasonic Flow meter was recorded.

The measured flow rate data (Q_{cul}), were depicted in Figure 4, versus the discharge values of the Ultrasonic Flow-Meter (Q_{ul}).

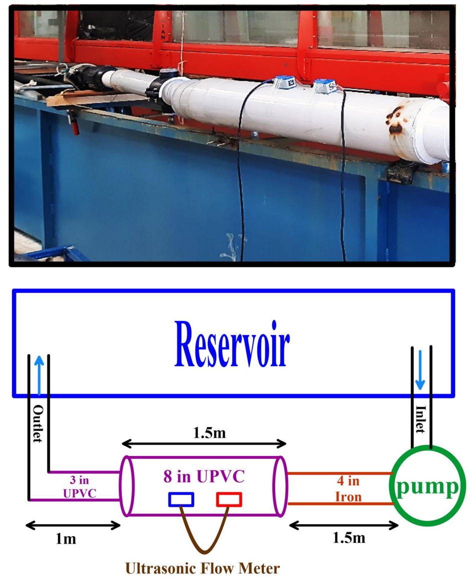

Figure 3. Experimental setup and pipeline to test the ultrasonic flow-meter performance.

According to the figure, the calibrated ultrasonic flow rate was obtained as follows:

$$Q_{cul} = 1.0923 Q_{ul}^{0.9436} \quad (1)$$

Employing Eq.1 and comparing with the measured data, the associated relative errors were calculated and the results were depicted in Figure 5. As shown, Equation (1) could be used to predict the flow rate with the relative errors limited in the range of ±4% with respect to the measured values.

The Taguchi method is one of the best experimental methodologies used to find the minimum number of experiments to be performed within the permissible limit of factors and levels (Meena *et al.,* 2018) In this study, for each pipe diameter, two factors of wall thickness and sensors' spacing were considered and each took three levels as listed in Table 1.

According to Taguchi orthogonal arrays, the required experimental runs to find the effect of the dependent variables are listed in Table 2.

According to Table 2, run number 5 in which both wall thickness and sensors' spacing were correctly adjusted, was considered the control treatment. Also, run

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Table 1. Tested parameters and the associated levels.

Parameter \ Level	1	2	3
Wall thickness	Decreased	Actual	Increased
Sensor spacing	Decreased	Actual	Increased

Table 2. Taguchi's experimental runs.

Run #	Wall thickness level	Sensors' spacing level
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

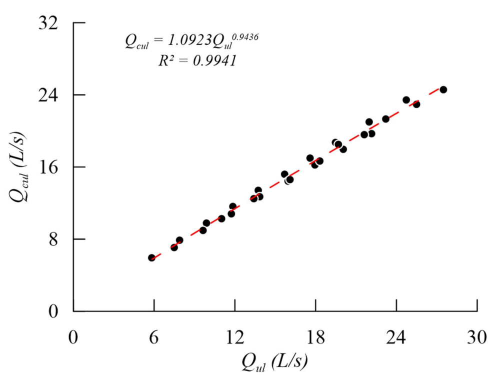

Figure 4. Measured flow rate data versus ultrasonic flow meter discharge values.

numbers 1, 3, 7, and 9 indicated the mixed effects of wall thickness and sensors' spacing. Run numbers (2 and 8) and (4 and 6) revealed the sole effects of sensors' spacing and wall thickness variations, respectively. Note that, from the practical point of view, the cases with the variations in both dependent parameters are rare, therefore, in this study, the mixed effects of

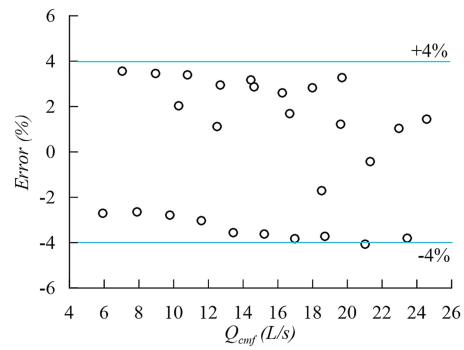

Figure 5. Relative error distribution associated with the calibrated ultrasonic flow meter.

the dependent parameters were not examined.

For a specific pipe characteristic, the input value of the pipe wall thickness was adjusted by ±1 mm changes from the actual value. Then, taking the sensors' spacing unchanged, the reading discharge values were compared with those obtained by the specific volume of water per unit time. A similar procedure was performed when the actual wall thickness of the pipe was considered as the input value and the sensor's spacing was changed. According to Table 2, the experiments performed in this study to evaluate the performance of the ultrasonic flow-meter are listed in Table 3.

RESULTS AND DISCUSSION

Sensitivity Analyses of the Input Parameters

Discharge variations due to any changes in either pipe wall thickness or sensors' spacing would affect the coefficients of Equation (1). Consequently, Equation (1) was reanalyzed for the experimental cases listed in Table 1. The results are illustrated in Figure 6 and Figure 7. The figures indicate clearly that variations of w_T and S_s, would affect the discharge measurements compared to the original calibrated discharge formula, i.e. Equation (1).

Sensitivity analysis is a useful method to show the effect of the input parameters. The sensitivity indicator used in this study was defined as the ratio of the relative discharge variations divided by the absolute relative change of the pipe wall thickness/sensors' spacing:

$$S_r = \frac{\Delta Q / Q}{\left| \Delta w_T / w_{actual} \right|} \tag{2}$$

$$S_r = \frac{\Delta Q / Q}{\left| \Delta S_s / S_{actual} \right|} \tag{3}$$

Where, S_r is the Sensitivity indicator, Q is flow rate, Δw_T is the pipe wall Thickness changes, w_{actual} is the actual value of the pipe wall thickness, ΔS_s is the Sensors' spacing changes, and S_{actual} is the actual value of the Sensors' spacing.

According to Figure 8, for all tested cases, the increase in pipe wall thickness would affect the ultrasonic performance

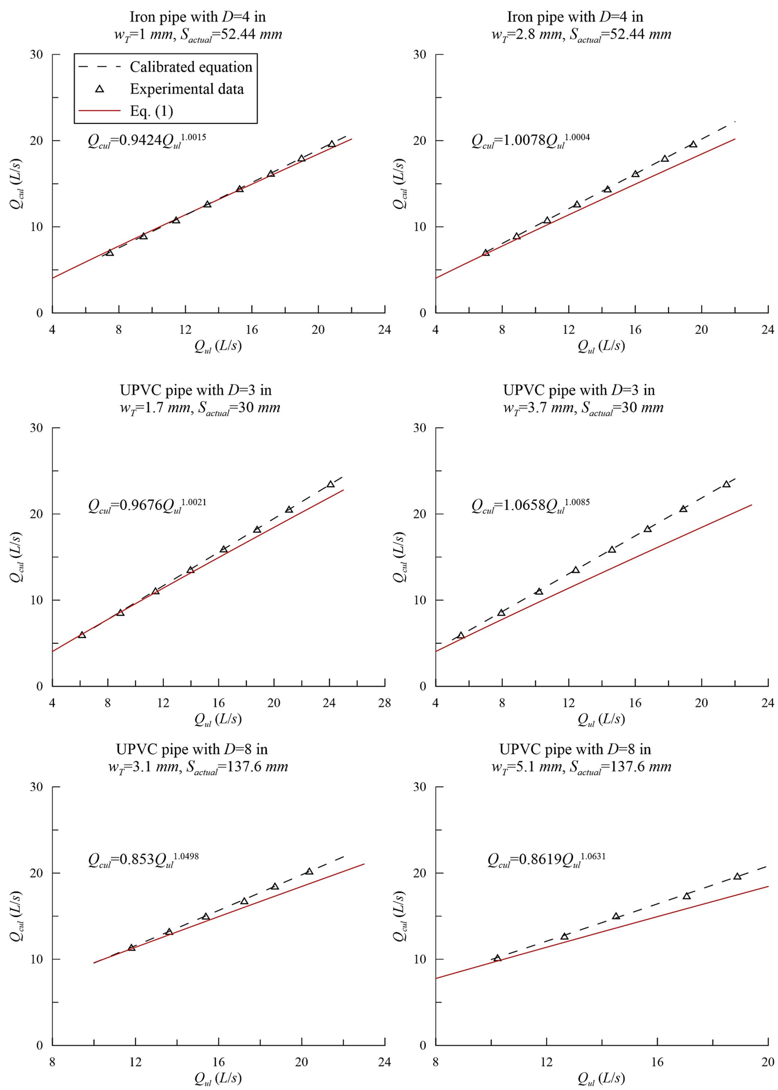

Figure 6. Calibrated discharge formula for different values of the input values of the pipe wall thickness.

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more than the cases with the decrease in wall thickness. It was also observed that the higher discharge values were associated with higher relative sensitivity values. As shown in Figure 9, the relative sensitivity variations that occurred due to the changing of the sensors' spacing were inconsistent. In general conclusion, the relative sensitivity indicator increased by increasing the flow rate. For the iron pipe with a diameter of 4 inches, no signal was detected when the sensors' spacing increased from 52.44 to 55.1 mm. For all other cases, signal quality was acceptable. For the UPVC pipe with a diameter of 3 inches, the accuracy of the ultrasonic flow

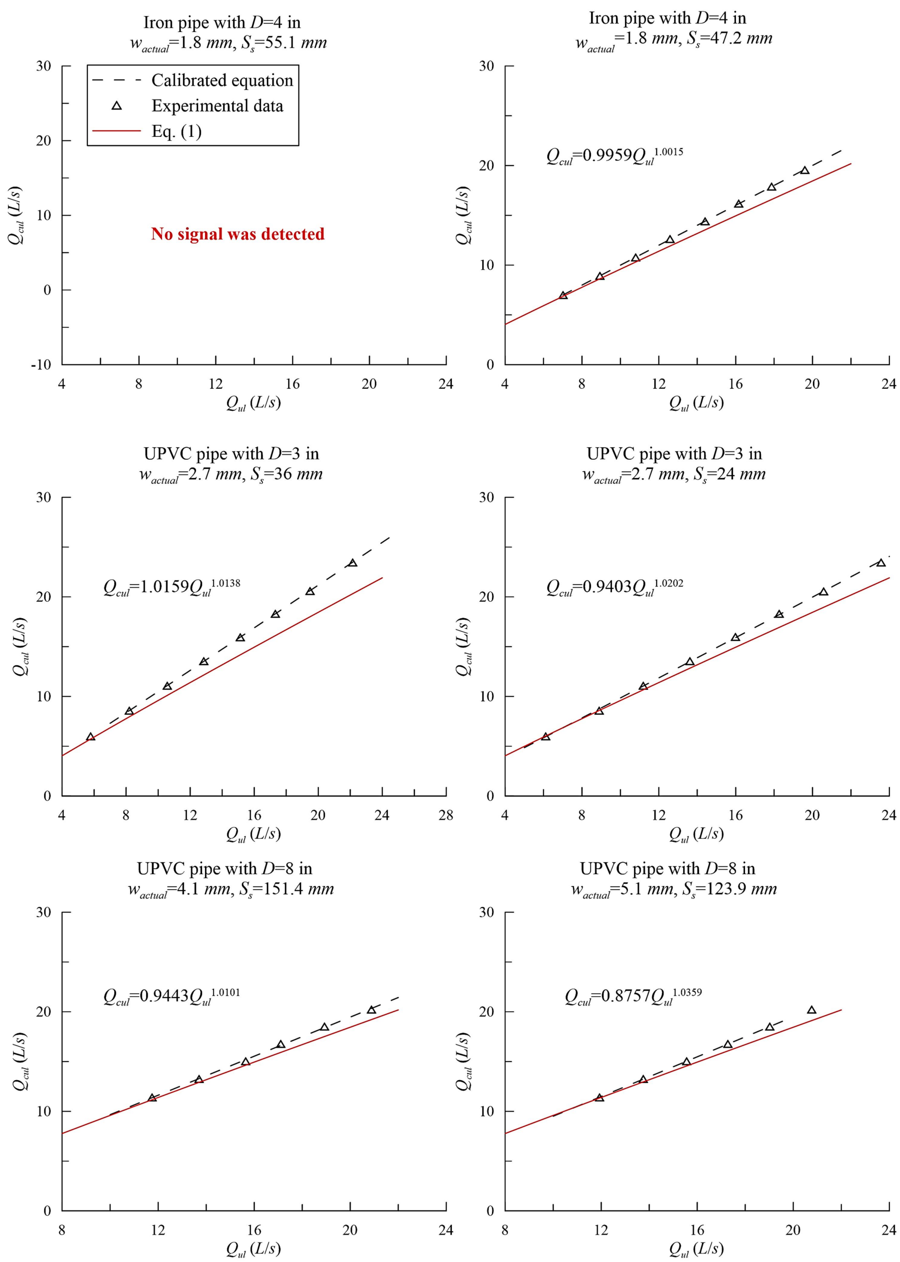

Figure 7. Calibrated discharge formula for different values of the input values of the sensors' spacing.

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Table 3. Descriptions of the experimental runs based on Taguchi methodology.

Pipe diameter (inch)	Material	Actual pipe wall thickness (mm)	Actual sensors' spacing (mm)	Input values of pipe wall thickness (mm)	Input values of sensors' spacing (mm)
4	Iron	1.8	52.44	1.8	47.2
4	Iron	1.8	52.44	1.8	55.1
4	Iron	1.8	52.44	1.8	52.44
4	Iron	1.8	52.44	1	52.44
4	Iron	1.8	52.44	2.8	52.44
3	UPVC	2.7	30	2.7	24
3	UPVC	2.7	30	2.7	36
3	UPVC	2.7	30	2.7	30
3	UPVC	2.7	30	1.7	30
3	UPVC	2.7	30	3.7	30
8	UPVC	4.1	137.6	4.1	123.9
8	UPVC	4.1	137.6	4.1	151.4
8	UPVC	4.1	137.6	4.1	137.6
8	UPVC	4.1	137.6	3.1	137.6
8	UPVC	4.1	137.6	5.1	137.6

meter was more sensitive to the sensors' spacing increase, while a mixed effect of the sensors' spacing was observed when the pipe diameter increased to 8 inches. More experimental cases should be tested to draw a general conclusion.

Sensitivity analyses revealed that both Sensors' spacing (S_s) and pipe wall Thickness (w_T) variations would affect the flow measurement accuracy. Also, field application of the ultrasonic flow meter would sometimes make it impossible to follow the installation tips exactly. Limited pipe length zone to install the sensors, pipe wall oxidation, and sedimentation inside the pipe are the most effective cases affecting the flow measurement accuracy. For the cases with a fixed sensors' location, the pipe wall thickness must be checked from time to time. W_T changes should be monitored and the associated recorded flow rate cases must be modified. Consequently, Eq. 1 needs to be recalibrated to include the effect of w_T and S_s. To this end, the following functional relationships were considered to incorporate the recalibrated discharge:

$$Q_{re} = f(Q_{cul}, w_T, w_{actual}, D, g) \qquad (4)$$

$$Q_{re} = f(Q_{cul}, s_s, s_{actual}, D, g) \qquad (5)$$

Where, Q_{re}, is the recalibrated ultrasonic flow rate, Q_{cul} should be calculated by Equation (1), and g is the acceleration due to gravity.

Applying the dimensional analyses and using the incomplete self-similarity theory Equations (6) and (7) take the following forms:

$$\frac{Q_{re}}{g^{0.5}D^{2.5}} = \alpha\left(\frac{Q_{cul}}{g^{0.5}D^{2.5}}\right)^{\beta}\left(\frac{w_T}{D}\right)^{\gamma}\left(\frac{w_{actual}}{D}\right)^{\eta} \qquad (6)$$

$$\frac{Q_{re}}{g^{0.5}D^{2.5}} = \alpha\left(\frac{Q_{cul}}{g^{0.5}D^{2.5}}\right)^{\beta}\left(\frac{s_s}{D}\right)^{\gamma}\left(\frac{s_{actual}}{D}\right)^{\eta} \qquad (7)$$

Where, α, β, γ, and η are constant parameters. Employing the experimental data obtained based on Table 1, the constant coefficients were determined and the results are listed in Table 4.

The relative error distribution associated with Equations (6) and (7) are depicted in Figure 10. As shown, the relative error of the recalibrated formulas were restricted in the ranges of ±6 and ±3% for the changes in the pipe wall thickness and sensors' spacing respectively.

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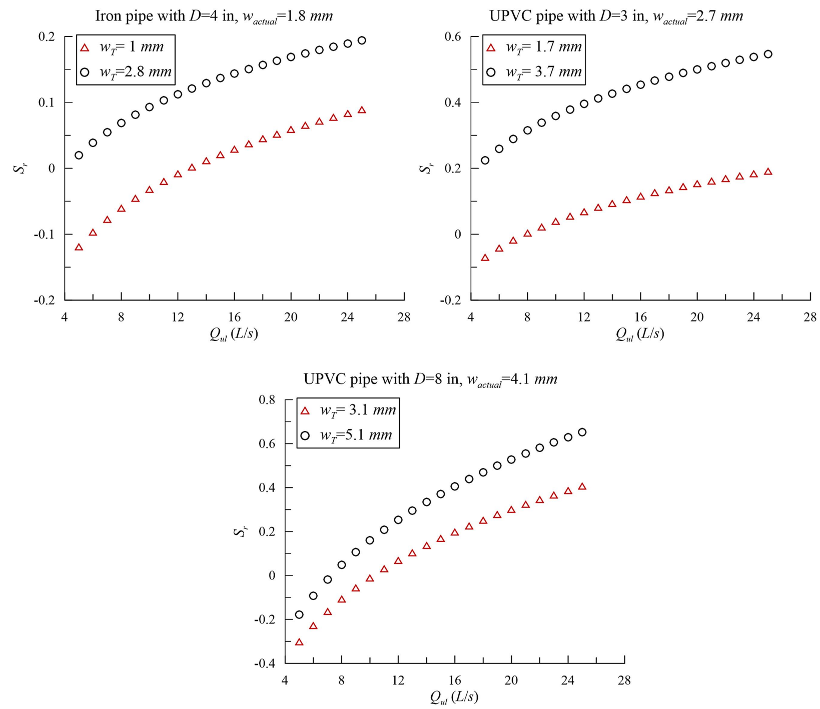

Figure 8. Sensitivity values in terms of the measured discharge for the variations of the pipe wall thickness with different pipe materials and diameters.

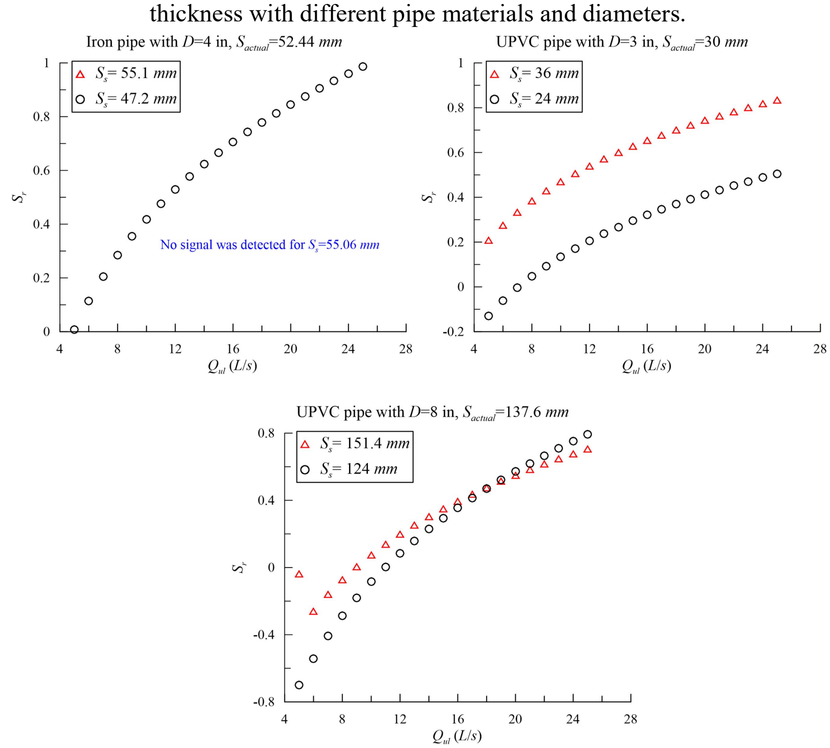

Figure 9. Sensitivity values in terms of the measured discharge for the variations of the sensors' spacing with different pipe materials and diameters.

Table 4. Constant parameters of Equations (6) and (7).

Variation source	α	β	γ	η
Pipe wall thickness, Equation (6)	1.23	1.0154	0.0866	–0.0436
Sensors’ spacing, Equation (7)	1.173	1.0807	0.15	–0.022

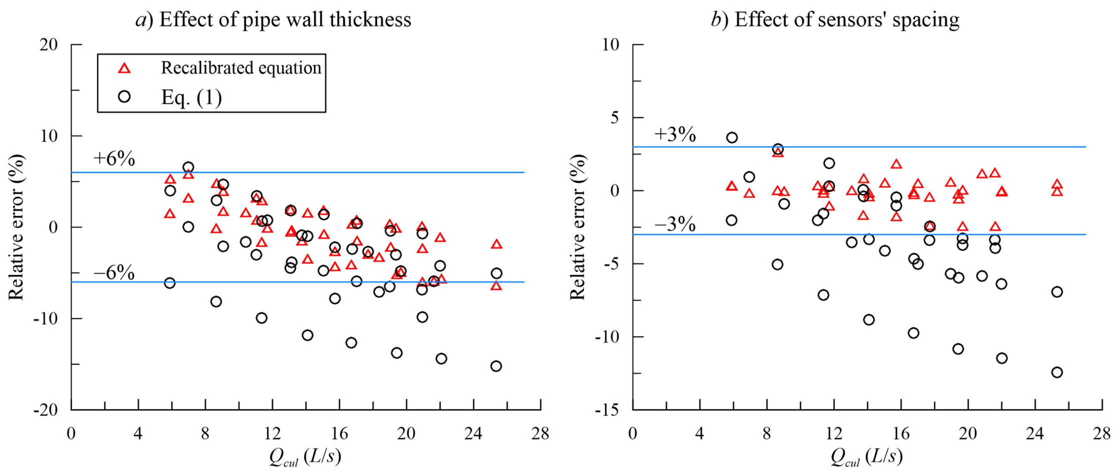

Figure 10. Relative error distribution due to (a) Pipe wall thickness and (b) Sensors’ spacing.

CONCLUSIONS

Field studies of the well depletion flow measurements revealed serious difficulties to set the required input parameters of the portable ultrasonic flow meters. Pipe wall oxidation, sedimentation, and inner coating are responsible for pipe wall thickness variations. It should be measured from time to time to adjust the portable flow meter input values. If not, a recalibrated formula is necessary. Experimental studies were performed to evaluate the effects of the pipe wall thickness and sensors’ spacing. Based on a detailed sensitivity analysis, the effects of the input parameters were quantified. Then, a recalibrating procedure was proposed. The associated relative error of the recalibrated formulas was restricted in the ranges of ±6 and ±3% for the changes in the pipe wall thickness and sensors’ spacing respectively.

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کاربرد میدانی فلومتر اولتراسونیک پرتابل بمنظور اندازه‌گیری دبی چاه

س. فکوری، و م. بی جن خان

چکیده

در این مقاله مشاهدات میدانی چالش های اندازه گیری جریان با استفاده از فلومترهای اولتراسونیک پرتابل ارائه شده است. بر این اساس ضخامت جدار لوله و فاصله بین سنسورها دو عامل مهم بر دقت اندازه گیری میدانی جریان شناسایی شدند. بمنظور ارزیابی تأثیر پارامترهای ورودی بر عملکرد فلومتر اولتراسونیک آزمایش های تجربی انجام شد. لوله های آهنی و پلی وینیل کلراید غیر پلاستیکی (UPVC) با قطرهای خارجی ۳، ٤ و ۸ اینچ مورد آزمایش قرار گرفتند. در تمام موارد افزایش ضخامت جدار لوله بیشتر از کاهش ضخامت جدار بر عملکرد فلومتر اولتراسونیک تأثیر می گذارد. برای فاصله سنسورها با تغییر جنس و قطر لوله اثر ترکیبی مشاهده شد. در نهایت معادله ای واسنجی شده برای بهبود اندازه‌گیری جریان پیشنهاد گردید.

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